# Predator Effects on Dense Zooplankton Aggregations in the Coastal Ocean

Kelly J. Benoit-Bird
College of Oceanic and Atmospheric Sciences, Oregon State University
104 COAS Admin Bldg
Corvallis, OR 97331
phone: (541) 737-2063 fax: (541) 737-2064 email: kbenoit@coas.oregonstate.edu

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http://oregonstate.edu/~benoitbk/thinlayers.html

## LONG-TERM GOALS

The distribution of organisms in the ocean is highly heterogeneous, influencing both sampling and ecological structure. The complex spatial and temporal structure of predators and prey affect one another. Numerous studies in pelagic systems have investigated the effects of prey distribution on predator behavior and studies in benthic habitats have revealed the significant impacts predators can have on prey distribution. However, primarily because of sampling difficulties, few studies have investigated the effects of predators on prey distribution in pelagic systems. In the last decade, advances in measurement capabilities have led to the discovery of plankton aggregations over continental shelves with vertical dimensions of tens of centimeters. These 'thin layers' can have a horizontal extent of several kilometers and may persist for days. Sharply distinct from the surrounding water column, the density of phytoplankton and zooplankton in these layers can be orders of magnitude higher than at surrounding depths. The discovery of these ubiquitous layers of plankton has opened up new possibilities in studying aggregation in the ocean. The long-term goal of this work is to understand the ecological importance of thin layers of plankton

## OBJECTIVES

- Determine the scales of aggregation of acoustic scatterers in the coastal ocean
- Understand the role of predation in determining the scales of these aggregations
- Assess the impact of the interaction of predators with aggregations of prey animals on the performance of acoustical and optical sensors.

## APPROACH

Extremely thin aggregations of zooplankton recently described in a number of coastal systems will be used as the experimental model for addressing these questions. These extremely thin aggregations persist over long time periods, are relatively predictable, and are being intensively studied in Monterey Bay, California as part of the ONR funded Layered Organization in the Coastal Ocean program (LOCO). I will work collaboratively with the investigators of this project to integrate my sampling approach into the existing program, adding a significant new component to the work while leveraging their resources to address the general biological questions of patchiness and scale in predator-prey interactions that are the focus of my research. The advantage of leveraging this project was the

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14. ABSTRACT

**The distribution of organisms in the ocean is highly heterogeneous, influencing both sampling and ecological structure. The complex spatial and temporal structure of predators and prey affect one another. Numerous studies in pelagic systems have investigated the effects of prey distribution on predator behavior and studies in benthic habitats have revealed the significant impacts predators can have on prey distribution. However, primarily because of sampling difficulties, few studies have investigated the effects of predators on prey distribution in pelagic systems. In the last decade, advances in measurement capabilities have led to the discovery of plankton aggregations over continental shelves with vertical dimensions of tens of centimeters. These ?thin layers? can have a horizontal extent of several kilometers and may persist for days. Sharply distinct from the surrounding water column, the density of phytoplankton and zooplankton in these layers can be orders of magnitude higher than at surrounding depths. The discovery of these ubiquitous layers of plankton has opened up new possibilities in studying aggregation in the ocean. The long-term goal of this work is to understand the ecological importance of thin layers of plankton**

15. SUBJECT TERMS

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availability of substantial vessel time, supplementary data, and concomitant sensing with other techniques.

*Specific methods:*
Continuously *map the distribution of acoustically scattering thin layers* looking for variations in depth and intensity using a five-frequency split-beam echosounder. Specifically, I will determine where thin layers are absent either through total loss in an area or in small gaps or breaks. Geostatistical techniques will be utilized to characterize the scales of aggregations, their spacing, and the features of edges.

*Compare* the results of synoptic surveys for *acoustically scattering and optically scattering thin layers*. This work will be done in collaboration with B. Concannon and J. Prentice who will be conducting concomitant LIDAR surveys. More than just comparing the two techniques, our goal is to determine if differences in acoustical and optical scattering can be related to the identity or distribution of organisms in these layers. We propose that the combination of optical and acoustic scattering can be used in a way analogous to looking at acoustic frequency spectra and using inverse processing techniques and may provide more information than adding additional frequencies to either technique alone.

Use a series of moored echosounders to *determine if larger scatterers* that may be consumers of organisms within thin aggregations *are regularly present over the shelf* in shallow waters either through advection of diel migrators or through active diel horizontal migration. I will compare the depths of these potential predators to the depths at which thin layers are detected at the same time during ongoing zooplankton process studies. Comparison of changes in the depth of both the thin layers and the larger animals may reveal tracking of the layers by its consumers.

Use a multibeam sonar to *detect relatively large individual, mobile acoustic scatters* both inside and outside thin aggregations of zooplankton. The data will be used to observe their behavior as well as to quantify the intensity and distribution of the thin layer to *determine if these larger animals appear to be foraging inside thin, horizontal layers* and what changes in the layers are correlated with their presence either as an immediate, observable response or statistical difference.

Utilize data to *predict acoustical and optical signal attenuation* as a function of scales of aggregations, their density, and composition. Dense aggregations of organisms can cause significant signal transmission loss and distortion. The variability in biological sources of scattering causes difficulties in predicting these losses. Data from the various approaches will be integrated to understand and predict how predation on dense aggregations can affect signal transmission in the coastal ocean.

## WORK COMPLETED

Data was collected over two field seasons in the summers of 2005 and 2006. Over the last year, substantial data analysis has been completed resulting in **two presentations** at the Acoustical Society of America Meeting:

Benoit-Bird, K.J., Cowles, T.J. “Acoustical and optical measurements provide evidence of ecological interactions in planktonic thin layers” 157$^{th}$ Meeting of the Acoustical Society of America. Portland, OR. May 18-22, 2009.

Kaltenberg, A.M., Benoit-Bird, K.J., Emmet, R. “Temporal patterns of fish and mesozooplankton near the Columbia River plume” 157th Meeting of the Acoustical Society of America. Portland, OR. May 18-22, 2009.

**and five peer-reviewed papers:**

Benoit-Bird, K.J., Cowles, T.J., Wingard, C.E. 2009 “Edge gradients provide evidence of ecological interactions in planktonic thin layers.” Limnology and Oceanography 54:1382-1392.

Benoit-Bird, K.J., Moline, M.A., Waluk, C.M, Robbins, I.C. “Integrated measurements of acoustical and optical thin layers I: Vertical scales of association.” Continental Shelf Research, Special Issue “The Structure and Dynamics of Thin Layers: The Layered Organization in the Coastal Ocean Experiment” Accepted for publication.

Moline, M.A., Benoit-Bird, K.J., Robbins, I.C. “Integrated measurements of acoustical and optical thin layers II: Critical horizontal length scales.” Continental Shelf Research, Special Issue “The Structure and Dynamics of Thin Layers: The Layered Organization in the Coastal Ocean Experiment” Accepted for publication.

Kaltenberg, A.M.* & Benoit-Bird, K.J. “Diel behavior of sardine and anchovy schools in the California Current System.” Marine Ecology Progress Series, Accepted for publication.

Benoit-Bird, K.J. “Three- and four-dimensional of zooplankton thin layers is affected by foraging fish, Marine Ecology Progress Series, Accepted for publication.

Two other papers from this work are currently in review.

## RESULTS

This work combined measurements from multiple platforms with acoustic instruments on moorings and on a ship and optics on a profiler and an autonomous underwater vehicle (AUV) to examine the relationships between fluorescent, bioluminescent, and acoustically scattering layers in Monterey Bay. We identified thin bioluminescent layers that were strongly correlated with acoustic scattering at the same depth but were part of vertically broad acoustic features, suggesting layers of unique composition inside larger biomass features. These compositional thin layers nested inside larger biomass features may be a common ecosystem component and are likely to have significant ecological impacts but are extremely difficult to identify as most approaches capable of the vertical scales of measurement necessary for the identification of sub-meter scale patterns assess bulk properties rather than specific layer composition. Measurements of multiple types of thin layers showed that the depth offset between thin phytoplankton and zooplankton layers was highly variable with some layers found at the same depth but others found up to 16 m apart. The vertical offset between phytoplankton and zooplankton thin layers was strongly predicted by the fraction of the water column fluorescence contained within a thin phytoplankton layer. Thin zooplankton layers were only vertically associated with thin phytoplankton layers when the phytoplankton in a layer accounted for more than about 18-20% of the water column chlorophyll. Trophic interactions were likely occurring between phytoplankton and zooplankton thin layers but phytoplankton thin layers were exploited by zooplankton only when they represented a large fraction of the available phytoplankton, suggesting zooplankton have some knowledge of the available food over the entire water column.

The horizontal extent of phytoplankton layers is likely an important factor contributing to the selective exploitation by zooplankton observed. While there is reasonable characterization of the vertical structure of these phenomena, the horizontal extent and critical horizontal length scale of variation has rarely been addressed. We evaluated the horizontal decorrelation length scales of the bio-optical and acoustic scattering layers themselves. Because biological layers are often decoupled from the physical structure of the water column, assessment of the variance within identified layers was appropriate. This differs from other studies in that physical parameters were not used as a basis for the layer definition. There was a significant diel pattern to the decorrelations length scale for acoustical layers with the more abundant nighttime layers showing less horizontal variability despite their smaller horizontal extent. While the length scales were related to the dynamic of each measurement made, there was a significant decrease in the de-correlationdecorrelation length scale in bio-optical parameters over the six years of study. The decrease in scale is shown to coincide with a documented shift in the plankton community in Monterey Bay and highlights the importance of considering plankton behavior and time of day with respect to scale, when studying layers. The changes in critical horizontal length scales also highlight the challenges of sampling these phenomena.

Previous work has suggested that thin layers are likely to have important ecological impacts, particularly affecting predator-prey interactions. Physical, optical, and acoustical data describing the distributions of phytoplankton, zooplankton, and small fish as well as gradients in the physical habitat were used to examine the interactions between plankton thin layers, their consumers, and the local physical forces they experience. The relationship between upper and lower edge gradients of a layer were used to define layer ‘shape’. The steepness of the vertical gradient on the top vs. the bottom of the plankton layer was correlated to the difference in the relative abundance of consumers above and below the layer. Phytoplankton layer gradients were steeper when more zooplankton were present on one side of the layer vs. the other while zooplankton layers were more diffuse when a greater number of fish were adjacent to one side of the layer than the other. Both layer types showed nearly symmetrical gradients when predators were in low abundance or absent. Predator-associated differences in phytoplankton and zooplankton layer shape were not correlated with vertical gradients in shear or mixing potential surrounding layers. In the absence of strong physical gradients, grazers can play an important role in structuring plankton thin layers. These observations likely represent one end of a continuum of biological and physical forcing responsible for formation and maintenance of thin plankton layers.

The potential attraction of fish to thin layers of zooplankton and the role of predation by fish in the formation and persistence of these layers were further assessed using three-dimensional sonar observations. Zooplankton were found in intense layers with vertical scales of 0.2-4.6 m with a mode of 2.2 m. These thin zooplankton layers had complex three-dimensional structure with significant, though gradual, undulations in their depth, thickness, and intensity. Fish spent significantly more time within zooplankton layers than expected, modifying their usual surface-coupled behavior when layers were present. Sonar tracks of individual fish showed them diving down through a zooplankton layer before spiraling slowly upwards through the layer. The upward portion of this behavior was correlated with a dramatic decrease in the intensity of zooplankton scattering at the scale of 1 m2, resulting in the appearance of holes in the layer. Continued observation of layers revealed that these holes slowly filled in with zooplankton an average of 4.3 minutes after the fish’s departure. Survey results show that when more fish were observed, more holes were observed and when larger fish were observed, larger holes were observed so that a total of up to 5% of a layer’s area could be comprised by holes. The thickness of layers was not affected by fish presence. Fish were attracted to zooplankton thin layers, showing

that thin layers in natural systems can have significant ecological effects; however, despite fish-associated changes to the structure of layers, they were resilient over time to the apparent foraging fish.

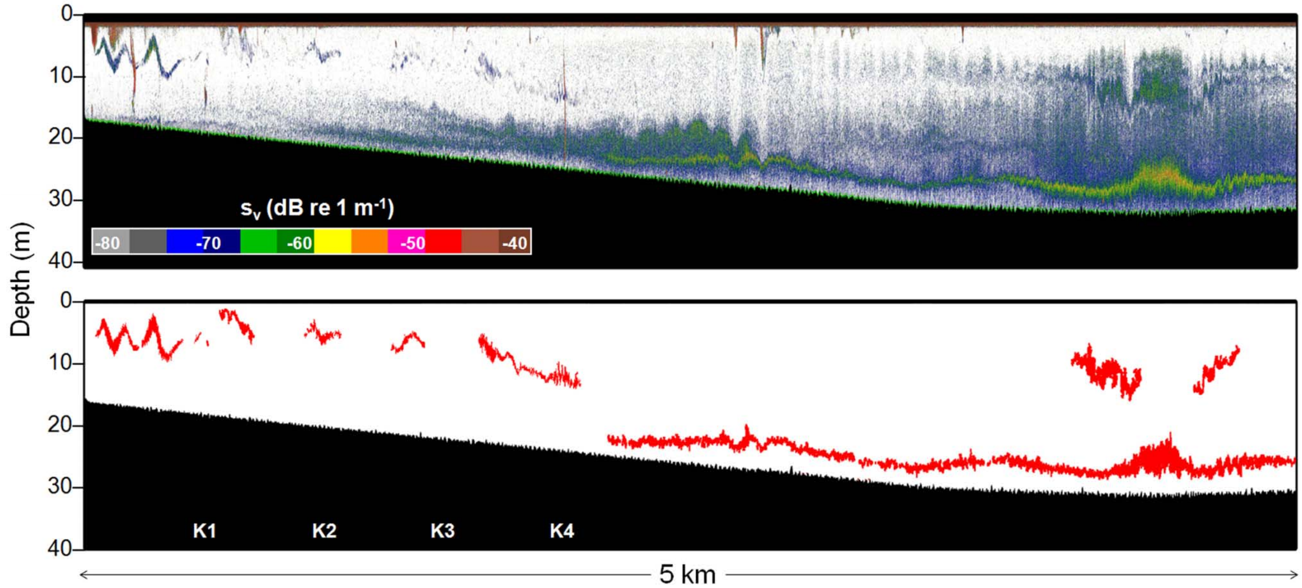


***Figure 1. The top panel shows an example transect of acoustic scattering at 120 kHz. The bottom panel shows the regions identified as containing an acoustic thin layer in red.***

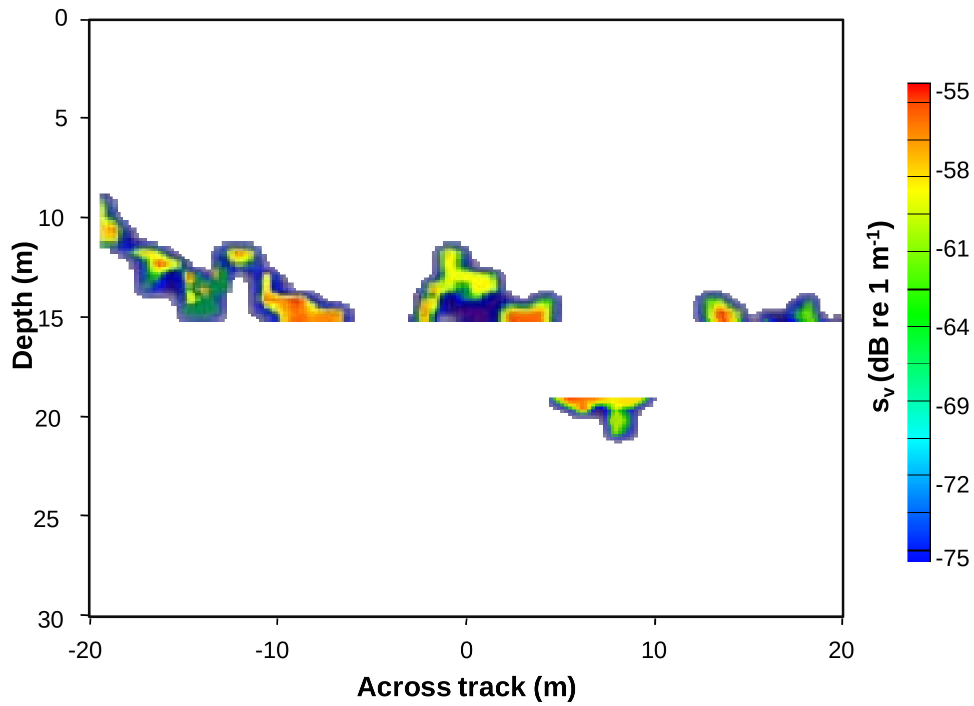


***Figure 2. Backscattering at 200kHz from a single ping from multibeam sonar. The seafloor is just visible at 30 m. A thin layer of zooplankton is evident between 10 and 20 meters. The layer is deeper to the right of the vessel and shallower to the left of the vessel.***

## IMPACT/APPLICATIONS

Patterns in biological distribution are often studied in relation to physical parameters and primary productivity. Numerous studies have demonstrated regulation of plankton by physical oceanographic processes. There has been limited research on biological causes of patchiness in the ocean: reproductive, interactions between parents and offspring; social, intraspecific signaling between individuals; and coactive, intraspecific actions such as competition, predation and parasitism. This work will provide information on how predators and prey interact in the coastal ocean and will permit us to determine how these interactions affect the formation and maintenance of thin layers. This is critical for understanding how organisms within thin layers affect our measurements and for making predictive models about their distribution. In addition, this work will provide comparable, ship based acoustic surveys for ongoing optical work, giving us a unique opportunity to understand the relationship between acoustical and optical scattering. Combination of these results with direct samples will enable us to integrate acoustical and optical data to examine the possibility of the identifying scattering sources with the synthesized sonar and lidar data.

## RELATED PROJECTS

This project is linked to those that are part of the *Layered Organization in the Coastal Ocean* DRI. Specifically, the projects of Holliday, Cowles, McManus, Prentice and Concannon.